Chapter 1
Properties of Fluids

FLUID MECHANICS & HYDRAULICS

Fluid Mechanics is a physical science dealing with the action of fluids at rest or in motion, and with applications and devices in engineering using fluids. Fluid mechanics can be subdivided into two major areas, *fluid statics*, which deals with fluids at rest, and *fluid dynamics*, concerned with fluids in motion. The term *hydrodynamics* is applied to the flow of liquids or to low-velocity gas flows where the gas can be considered as being essentially incompressible.

Hydraulics deals with the application of fluid mechanics to engineering devices involving liquids, usually water or oil. Hydraulics deals with such problems as the flow of fluids through pipes or in open channels, the design of storage dams, pumps, and water turbines, and with other devices for the control or use of liquids, such as nozzles, valves, jets, and flowmeters.

TYPES OF FLUID

Fluids are generally divided into two categories: ideal fluids and real fluids.

Ideal fluids

- Assumed to have no viscosity (and hence, no resistance to shear)
- Incompressible
- Have uniform velocity when flowing
- No friction between moving layers of fluid
- No eddy currents or turbulence

Real fluids

- Exhibit infinite viscosities
- Non-uniform velocity distribution when flowing
- Compressible
- Experience friction and turbulence in flow

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Real fluids are further divided into *Newtonian fluids* and *non-Newtonian fluids.*

Most fluid problems assume real fluids with Newtonian characteristics for convenience. This assumption is appropriate for water, air, gases, steam, and other simple fluids like alcohol, gasoline, acid solutions, etc. However, slurries, pastes, gels, suspensions may not behave according to simple fluid relationships.

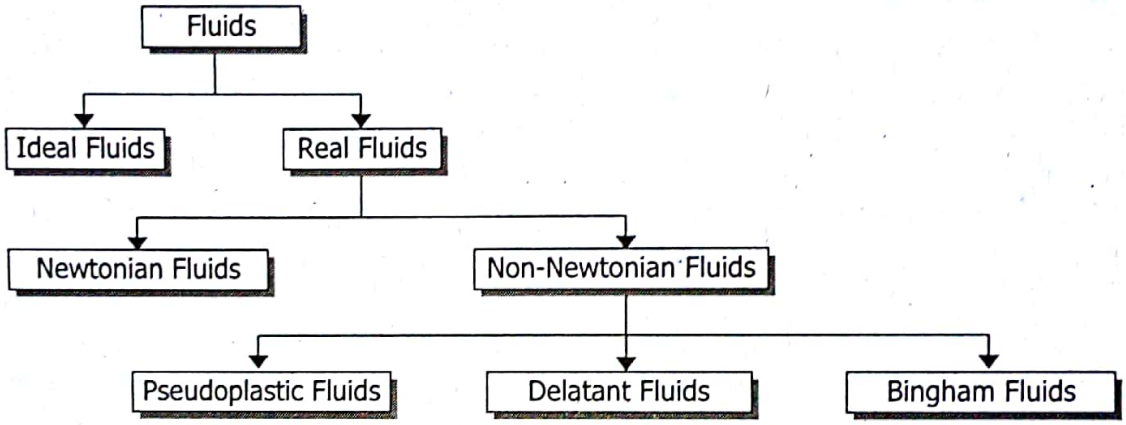

Figure 1 - 1: Types of fluid

MASS DENSITY, ρ (RHO)

The density of a fluid is its mass per unit of volume.

$$\rho = \frac{\text{mass of fluid, } M}{\text{volume, } V} \qquad \text{Eq. 1 - 1}$$

Units:

English	:	slugs/ft³	Note: $\rho_{slugs} = \rho_{lbm}/g$
Metric	:	gram/cm³	
SI	:	kg/m³	

For an ideal gas, its density can be found from the specific gas constant and ideal gas law:

$$\rho = \frac{p}{RT} \qquad \text{Eq. 1 - 2}$$

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where: p = absolute pressure of gas in Pa
R = gas constant Joule / kg-°K
For air:
R = 287 J/kg - °K
R = 1,716 lb-ft/slug-°R
T = absolute temperature in °Kelvin
°K = °C + 273
°R = °F + 460

Table 1 - 1: Approximate Room-Temperature Densities of Common Fluids

Fluid	ρ in kg/m³
Air (STP)	1.29
Air (21°F, a 1tm)	1.20
Alcohol	790
Ammonia	602
Gasoline	720
Glycerin	1,260
Mercury	13,600
Water	1,000

SPECIFIC VOLUME, V_s

Specific volume, V_s, is the volume occupied by a unit mass of fluid.

$$V_s = \frac{1}{\rho} \qquad \text{Eq. 1 - 3}$$

UNIT WEIGHT OR SPECIFIC WEIGHT, γ

Specific weight or unit weight, γ, is the weight of a unit volume of a fluid.

$$\gamma = \frac{\text{weight of fluid, } W}{\text{volume, } V} \qquad \text{Eq. 1 - 4}$$

$$\gamma = \rho g \qquad \text{Eq. 1 - 5}$$

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Units:

English : lb/ft^3
Metric : $dyne/cm^3$
SI : N/m^3 or kN/m^3

SPECIFIC GRAVITY

Specific gravity, s, is a dimensionless ratio of a fluid's density to some standard reference density. For liquids and solids, the reference density is water at 4° C (39.2° F).

$$s = \frac{\rho_{liquid}}{\rho_{water}} \qquad \text{Eq. 1 - 6}$$

In gases, the standard reference to calculate the specific gravity is the density of air.

$$s = \frac{\rho_{gas}}{\rho_{air}} \qquad \text{Eq. 1 - 7}$$

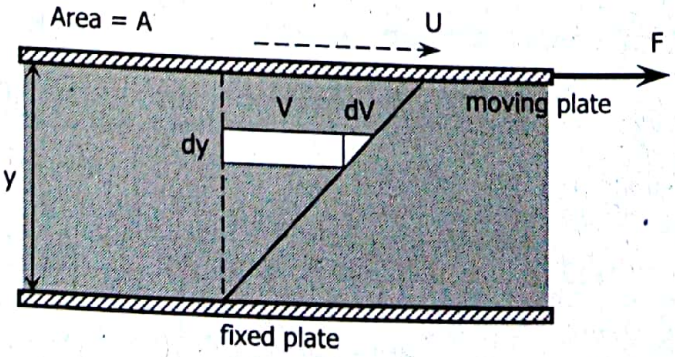
For water at 4°C:

$\gamma = 62.4\ lb/ft^3 = 9.81\ kN/m^3$
$\rho = 1.94\ slugs/ft^3 = 1000\ kg/m^3$
$s = 1.0$

VISCOSITY, μ (MU)

The property of a fluid which determines the amount of its resistance to shearing forces. A perfect fluid would have no viscosity.

Consider two large, parallel plates at a small distance y apart, the space between them being filled with a fluid. Consider the upper plate to be subject to a force F so as to move with a constant velocity U. The fluid in contact with



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the upper plate will adhere to it and will move with the same velocity U while the fluid in contact with the fixed plate will have a zero velocity. For small values of U and y, the velocity gradient can be assumed to be a straight line and F varies as A, U and y as:

$$F \propto \frac{AU}{y} \quad \text{or} \quad \frac{F}{A} \propto \frac{U}{y}$$

but $\frac{U}{y} = \frac{dV}{dy}$ (from the figure)

$\frac{F}{A}$ = Shearing stress, τ

$$\tau \propto \frac{dV}{dy} \quad \text{or} \quad \tau = k\frac{dV}{dy}$$

where the constant of proportionality k is called the dynamic of absolute viscosity denoted as μ.

$$\tau = \mu\frac{dV}{dy}$$

$$\mu = \frac{\tau}{dV/dy} \qquad \text{Eq. 1 - 8}$$

where:

τ = shear stress in lb/ft² or Pa
μ = absolute viscosity in lb sec/ft² (poises) or Pa-sec.
y = distance between the plates in ft or m
U = velocity in ft/s or m/s

KINEMATIC VISCOSITY ν (NU)

Kinematic viscosity is the ratio of the dynamic viscosity of the fluid, μ, to its mass density, ρ.

$$\nu = \frac{\mu}{\rho} \qquad \text{Eq. 1 - 9}$$

where:

μ = absolute viscosity in Pa-sec.
ρ = density in kg/m³

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Table 1 - 2: Common Units of Viscosity

System	Absolute, μ	Kinematic, ν
English	lb-sec/ft² (slug/ft-sec)	ft²/sec
Metric	dyne-s/cm² (poise)	cm²/s (stoke)
S.I.	Pa-s (N-s/m²)	m²/s

Note:

1 poise = 1 dyne·s/cm² = 0.1 Pa-sec (1 dyne = 10^{-5} N)

1 stoke = 0.0001 m²/s

SURFACE TENSION σ (SIGMA)

The membrane of "skin" that seems to form on the free surface of a fluid is due to the intermolecular cohesive forces, and is known as *surface tension*. Surface tension is the reason that insects are able to sit on water and a needle is able to float on it. Surface tension also causes bubbles and droplets to take on a spherical shape, since any other shape would have more surface area per unit volume.

Pressure inside a Droplet of Liquid:

$$p = \frac{4\sigma}{d} \qquad \text{Eq. 1 - 10}$$

where:

σ = surface tension in N/m

d = diameter of the droplet in m

p = gage pressure in Pa

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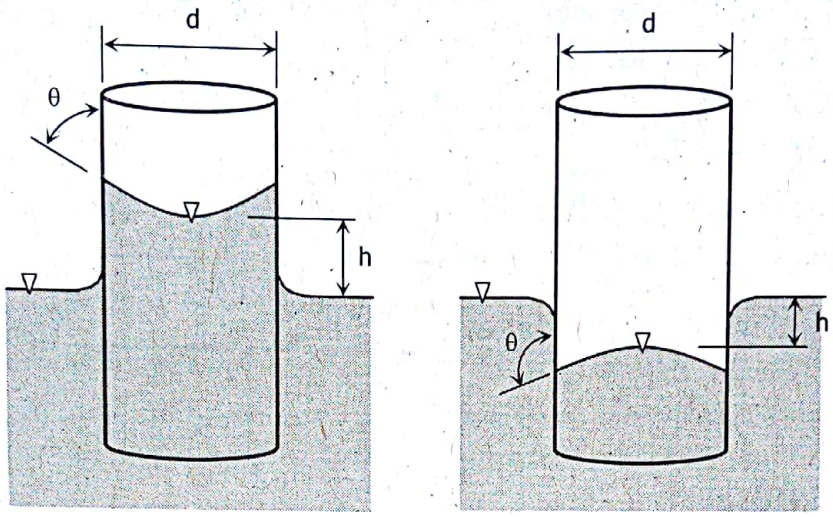
Capillarity



(a) Adhesion > cohesion (b) Cohesion > adhesion

Capillarity (*Capillary action*) is the name given to the behavior of the liquid in a thin-bore tube. The rise or fall or a fluid in a capillary tube is caused by surface tension and depends on the relative magnitudes of the cohesion of the liquid and the adhesion of the liquid to the walls of the containing vessel. Liquids rise in tubes they wet (adhesion > cohesion) and fall in tubes they do not wet (cohesion > adhesion). Capillary is important when using tubes smaller than about 3/8 inch (9.5 mm) in diameter.

$$h = \frac{4\sigma \cos\theta}{\gamma d} \qquad \text{Eq. 1 - 11}$$

For complete wetting, as with water on clean glass, the angle θ is 0°. Hence the formula becomes

$$h = \frac{4\sigma}{\gamma d} \qquad \text{Eq. 1 - 12}$$

where:

h = capillary rise or depression in m
γ = unit weight in N/m^3
d = diameter of the tube in m
σ = surface tension in Pa

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Table 1 - 3: Contact Angles, θ

Materials	Angle, θ
mercury-glass	140°
water-paraffin	107°
water-silver	90°
kerosene-glass	26°
glycerin-glass	19°
water-glass	0°
ethyl alcohol-glass	0°

COMPRESSIBILITY, β

Compressibility (also known as the *coefficient of compressibility*) is the fractional change in the volume of a fluid per unit change in pressure in a constant-temperature process.

$$\beta = \frac{-\frac{\Delta V}{V}}{\Delta p} = \frac{1}{E_B} \qquad \text{Eq. 1 - 13}$$

$$\text{or } \beta = -\frac{dV/V}{dp} \qquad \text{Eq. 1 - 14}$$

where:

ΔV = change in volume
V = original volume
Δp = change in pressure
dV/V = change in volume (usually in percent)

BULK MODULUS OF ELASTICITY, E_B

The bulk modulus of elasticity of the fluid expresses the compressibility of the fluid. It is the ratio of the change in unit pressure to the corresponding volume change per unit of volume.

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$$E_B = \frac{\text{stress}}{\text{strain}} = \frac{\Delta p}{\frac{\Delta V}{V}} \qquad \text{Eq. 1 - 15}$$

$$\text{or } E_B = -\frac{dp}{dV/V} \qquad \text{Eq. 1 - 16}$$

PRESSURE DISTURBANCES

Pressure disturbances imposed on a fluid move in waves. The velocity or celerity of pressure wave (also known as *acoustical* or *sonic velocity*) is expressed as:

$$c = \sqrt{\frac{E_B}{\rho}} = \sqrt{\frac{1}{\beta\rho}} \qquad \text{Eq. 1 - 17}$$

PROPERTY CHANGES IN IDEAL GAS

For any ideal gas experiencing any process, the equation of state is given by:

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \qquad \text{Eq. 1 - 18}$$

When temperature is held constant, Eq. 1 - 18 reduces to (*Boyle's Law*)

$$p_1 V_1 = p_2 V_2 \qquad \text{Eq. 1 - 19}$$

When temperature is held constant (isothermal condition), Eq. 1 - 18 reduces to (*Charle's Law*)

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \qquad \text{Eq. 1 - 20}$$

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For Adiabatic or Isentropic Conditions (no heat exchanged)

$$p_1 V_1^k = p_2 V_2^k \qquad \text{Eq. 1 - 21}$$

$$\text{or} \quad \left(\frac{V_1}{V_2}\right)^k = \frac{p_2}{p_1} = \text{Constant} \qquad \text{Eq. 1 - 22}$$

$$\text{and} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \qquad \text{Eq. 1 - 23}$$

where:

p_1 = initial absolute pressure of gas
p_2 = final absolute pressure of gas
V_1 = initial volume of gas
V_2 = final volume of gas
T_1 = initial absolute temperature of gas in °K (°K = °C + 273)
T_2 = final absolute temperature of gas in °K
k = ratio of the specific heat at constant pressure to the specific heat at constant volume. Also known as adiabatic exponent.

VAPOR PRESSURE

Molecular activity in a liquid will allow some of the molecules to escape the liquid surface. Molecules of the vapor also condense back into the liquid. The vaporization and condensation at constant temperature are equilibrium processes. The equilibrium pressure exerted by these free molecules is known as the *vapor pressure* or *saturation pressure*.

Some liquids, such as propane, butane, ammonia, and Freon, have significant vapor pressure at normal temperatures. Liquids near their boiling point or that vaporizes easily are said to *volatile liquids*. Other liquids such as mercury, have insignificant vapor pressures at the same temperature. Liquids with low vapor pressure are used in accurate barometers.

The tendency toward vaporization is dependent on the temperature of the liquid. *Boiling* occurs when the liquid temperature is increased to the point that the vapor pressure is equal to the local ambient (surrounding) pressure. Thus, a liquid's boiling temperature depends on the local ambient pressure, as well as the liquid's tendency to vaporize.

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Table 1 - 4: Typical Vapor Pressures

Fluid	kPa, 20°C
mercury	0.000173
turpentine	0.0534
water	2.34
ethyl alcohol	5.86
ether	58.9
butane	218
Freon-12	584
propane	855
ammonia	888

Solved Problems

Problem 1 - 1

A reservoir of glycerin has a mass of 1,200 kg and a volume of 0.952 cu. m. Find its (*a*) weight, *W*, (*b*) unit weight, γ, (*c*) mass density, ρ, and (*d*) specific gravity (*s*).

Solution

(*a*) Weight, $W = M\,g$

$= (1{,}200)(9.81)$

Weight, $W =$ **11,772 N** or **11.772 kN**

(*b*) Unit weight, $\gamma = \dfrac{W}{V}$

$= \dfrac{11.772}{0.952}$

Unit weight, $\gamma =$ **12.366 kN/m³**

(*c*) Density, $\rho = \dfrac{M}{V}$

Density, $\rho = \dfrac{1200}{0.952}$

Density, $\rho =$ **1,260.5 kg/m³**

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